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Effect of insolation variations on vegetations of the Eurasian subarctic during the Holocene

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Abstract. Variation of the insolation is one of the global factors which determine the Earth's climate. Multi-periodic variations of the insolation determine the cyclicity of the Earth's climate. The aim of the investigation is the estimation of the insolation variations influence on vegetations of the Urals and West Siberia subarctic during the Holocene. The calculation of insolation in the Eurasian Subarctic for the Holocene is carried out based on the solution La2004 for the long-period evolution of the Earth's orbit. We have estimated the insolation for the latitudes from 55° to 70° N. We have considered the mean daily and mean monthly insolation over 12 ka BP. We assess changes of the insolation in the Eurasian subarctic under the influence of such factor as the topography evolution. The surface topography was analyzed for the recent period (in the Urals and West Siberia) and the Pliocene epoch (in West Siberia). An assessment of the difference in the corresponding digital elevation models showed that the subsidence of the crust took place in West Siberia (the median value of the difference between the digital elevation models was 230.7 m above sea level). The intensity of erosion processes increased in a southerly direction. We have shown that an increase in the number of autumn's months with high insolation correlates with the taiga biome 4 thousand years ago to wider territories than 8 thousand years ago.

1. Introduction

Variation of the insolation is one of the global factors which determine the Earth's climate. Multi-periodic variations of the insolation determine the cyclicity of the Earth's climate. Spatio-temporal dynamics of insolation leads to heterogeneity in local energy and water balance, which determines environmental factors such as air and soil temperature, evapotranspiration, snowmelt regime, winds, soil moisture, and light available for photosynthesis [1 – 3].

Important factors influencing the variation of the insolation are the orbital motion of the Earth and topographic heterogeneities and surface features (elevation, slope, aspect, and shadows cast by topographic objects). Therefore, in the case of long-term modeling of insolation, it is necessary to take into account the evolution of the Earth's orbit and the deformation of the crust under the influence of tectonic processes and erosion.



A marker of climate change affecting biome change is vegetation. As a rule, it is changed in vegetation (or other indicators associated with it) that are considered as indirect indicators of climate change.

The study aims to assess the change in insolation rates and the change in the type of vegetation of the subarctic of the Urals and Western Siberia in the Holocene.

We estimate the insolation variations influence the climate of the Urals and West Siberia subarctic during the Holocene. We assess changes of the insolation in the Eurasian subarctic under the influence of the crustal deformation. We study the impact of an increase in the number of autumn's months with high insolation to biomes.

2. Methods

The calculation of insolation at the top of the Earth's atmosphere in the Eurasian Subarctic for the Holocene is carried out based on the solution La2004 for the long-period evolution of the Earth's orbit [4]. The orbital model takes into account eight major planets of the Solar System and the dwarf planet Pluto. The post-Newtonian general relativity corrections of order $1/c^2$ due to the Sun are included (where c is the light velocity). The Moon is treated as a separate object. In order to obtain a realistic evolution of the Earth–Moon System, which also takes into account the most important coefficient (dynamical form-factor of the Sun J_{2S}) in the gravitational potential of the Earth and of the Moon, and the tidal dissipation in the Earth–Moon System. The precession and obliquity equations for the Earth and the evolution of its rotation period is also integrated at the same time. That model is a numerical solution for the full Solar System with the Earth's precession model based on Lunar Laser Ranging observations, orbital solution valid from -50 to $+20$ Ma BP.

One of the objectives of this study was to assess changes in the surface insolation in the Eurasian subarctic under the influence of the crustal deformation. The surface topography was analyzed for the recent period (the Urals and West Siberia) and for the Pliocene epoch (West Siberia). The digital elevation model (DEM) for the Pliocene (Pre-Yamalian time) was built based on a paleogeomorphological map at a scale of 1: 4,000,000 [5]. DEM of the Pliocene and the modern period were divided by parallels into segments of 1° . For each segment, annual solar radiation was calculated (365 days for a non-leap year) at monthly intervals. The sum of direct and diffuse radiation was determined using the methods of the hemispherical viewshed algorithm [6, 7]. This algorithm takes into account viewshed, surface orientation, elevation, and atmospheric conditions [8]. Since the cloud-cover data for the Pliocene were not available, we used constants for atmospheric transmissivity and diffuse proportion parameters for generally clear sky conditions. Further, these segments were combined into single surface insolation models for the two analyzed periods, and an estimate of the transformation of the amount of solar radiation due to changes in the topography was obtained.

To calculate biomes, we used the results of pollen analysis of 24 sections of peatlands in the territory of the Middle, Northern, Subpolar, Polar Urals and South Yamal (figure 1). Data published in [9–26]. For calculations, we used the initial tables of pollen spectra: the percentage of pollen and spores of each sample, where the sum of pollen from trees and shrubs was taken as 100%. All examined sections are dated to ^{14}C , which allowed us to build depth-age models for each section Clam 2.0 [27]. The dates are calibrated in the same program [28]. Reconstructions were carried out according to time sections of the Holocene with an interval of 1000 years, respectively, for a time of 11,000 years ago, 10,000, 9,000, ..., 0 years ago. According to the depth-age graphs in each section, samples were identified from a depth corresponding to a certain age. Based on them, biomes were calculated according to the method described by C. Prentice [29, 30]. A biome having the maximum affinity for the pollen spectrum of the sample corresponding to a given time slice was entered into the summary table. According to the coordinates of the sections, the reconstructed biomes were plotted on the map of the corresponding time slice in the form of conditional points colored in a specific color for each biome. Modern biomes reconstructed from surface pollen spectrum are compared with the map “Biomes of Russia” [31].

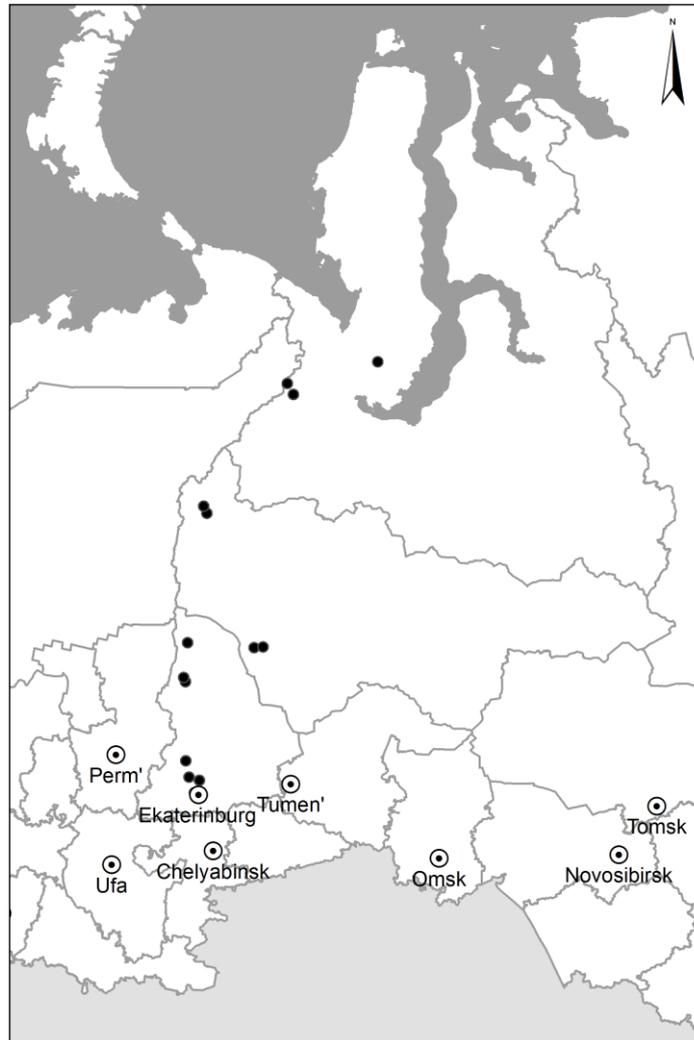


Figure 1. Sites of sections of peatlands in the territory of the Middle, Northern, Subpolar, Polar Urals, and South Yamal.

3. Results

We have estimated the insolation at the top of the Earth's atmosphere for the latitudes from 55° to 70° N. We have considered the mean monthly (figures 2 and 3) and mean daily (figure 4) insolation over 12 ka BP. The mean monthly insolation weakly depends on time for months from December to March (figures 3f and 2a–2c). The mean monthly insolation moderate depends on time in April (figure 2d) and for months from September to November (figures 3c–3e). The mean monthly insolation is minimal in April (figure 2d) near 5 ka BP, in May (figure 2e) near 4 ka BP and maximal in August (figure 3b) near 5 ka BP, in September (figure 3c) near 4 ka BP, in October (figure 3d) and November (figure 3e) near 2 ka BP. The mean monthly insolation strength depends on time for months from May to August (figures 2e, 2f, 3a, and 3b). The mean monthly insolation in June (figure 2f) and July (figure 3a) decreases over time from 12 ka BP to the present day.

The change of the mean daily insolation on 21 June (figure 4a) is similar for different latitudes, except the last 1 ka when the insolation for the latitudes 65° and 70° N decreases more fastest that one for more southern latitudes. The mean daily insolation on 21 July (figure 4b) for the latitude 70° N is varied between the values for latitudes 60° and 65° N.

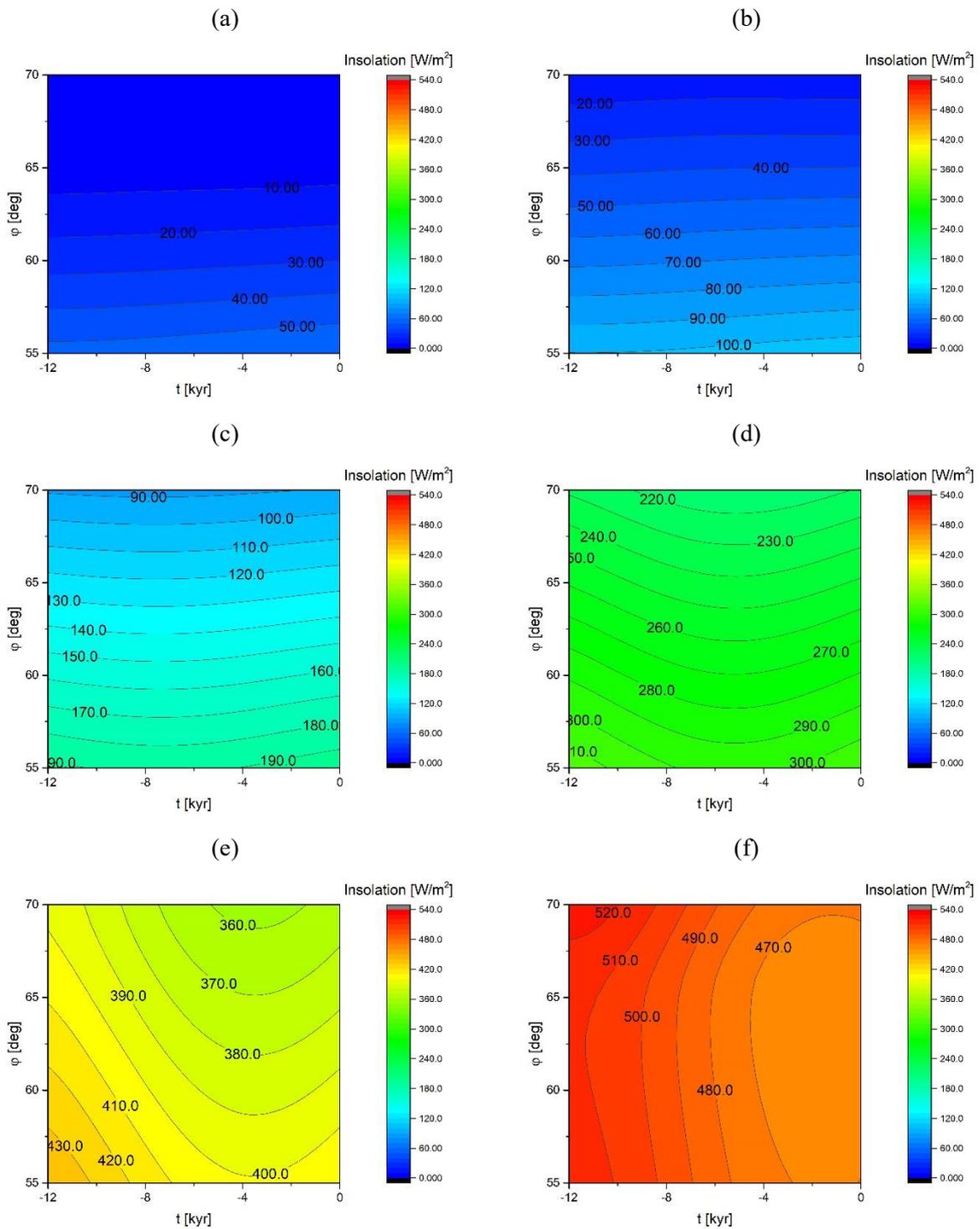


Figure 2. The mean monthly insolation for the latitudes from 55° to 70° N in: (a) January, (b) February, (c) March, (d) April, (e) May, (f) June

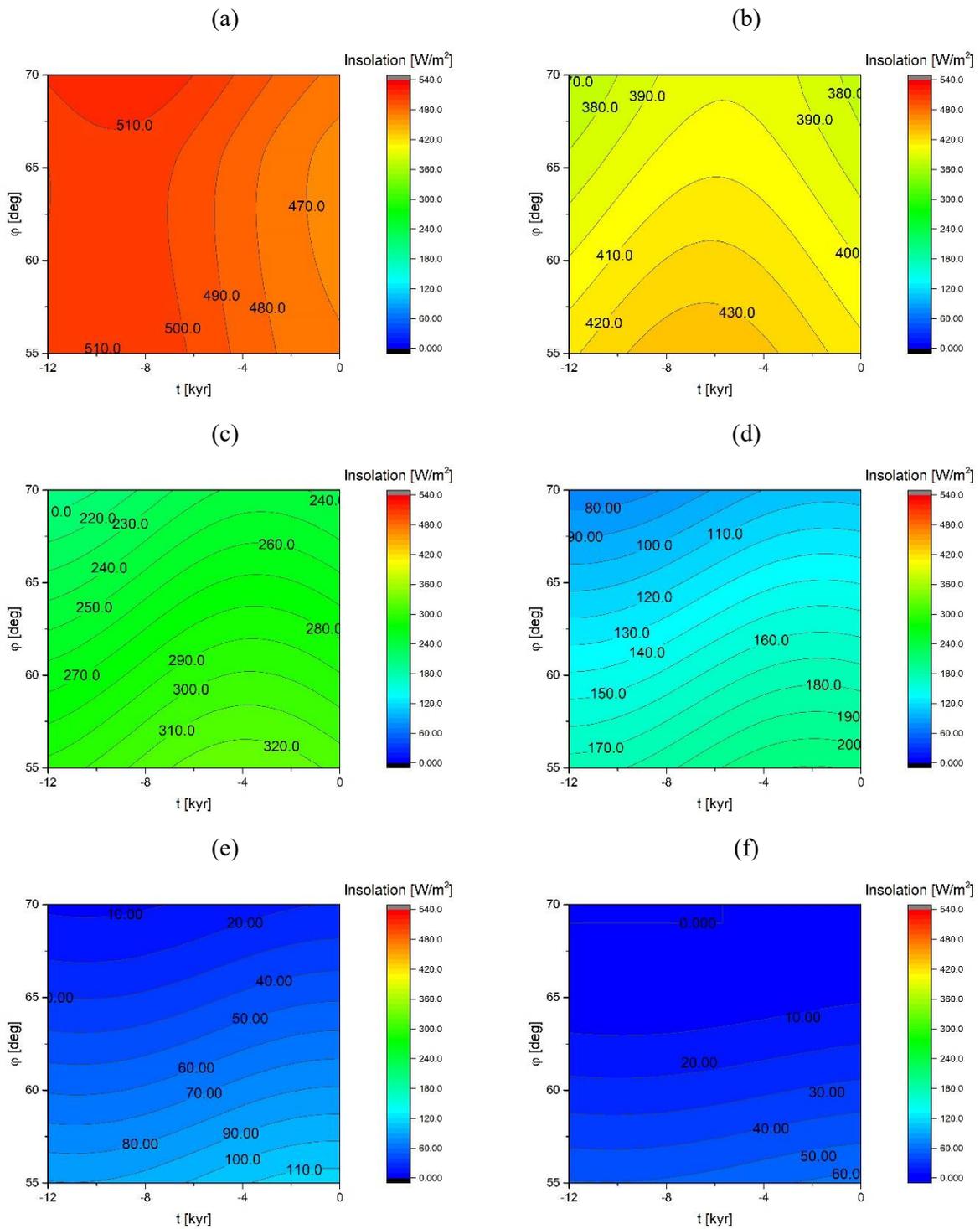


Figure 3. The mean monthly insolation for the latitudes from 55° to 70° N in: (a) July, (b) August, (c) September, (d) October, (e) November, (f) December

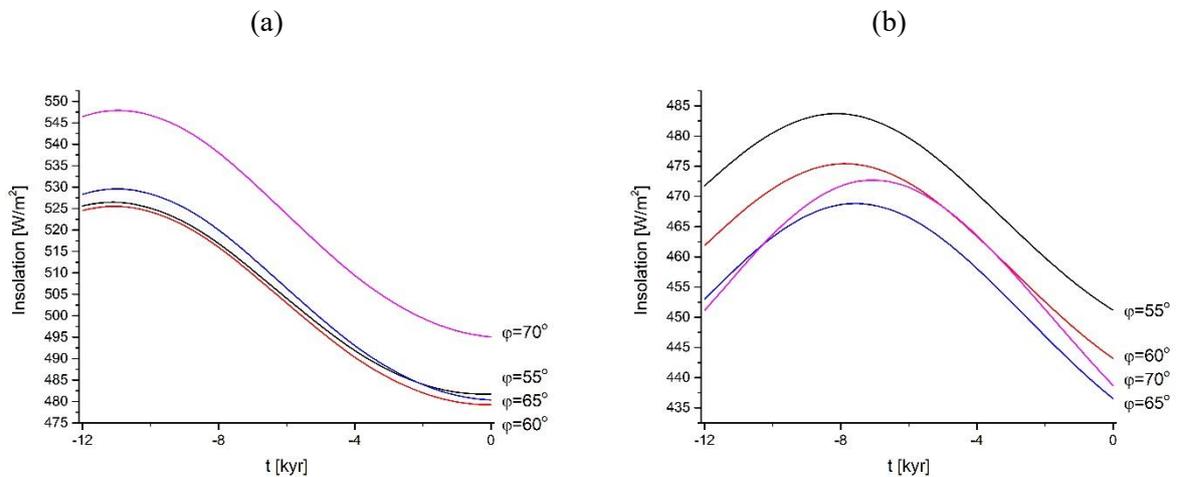


Figure 4. The mean daily insolation on: (a) 21 June, (b) 21 July.

The changes in the annual surface insolation in the Eurasian subarctic under the influence of the crustal deformation is analyzed for the recent period (in the Urals and West Siberia, see figures 5 and 6a) and for the Pliocene epoch (in West Siberia, see figure 6b). A comparison of insolation maps of the Pliocene epoch with modern data (figure 6) showed that in most West Siberia the solar radiation was higher at the beginning of the period under consideration. The median value of the difference in annual surface insolation between the Pliocene and the recent period was 22.3 kW/m². The presence of small separate areas with negative values of the difference in insolation (figure 6c) noted near rivers. This can be explained by both the mismatch of river channels and the difference in the depth of incidence of watercourses recorded for different geological epochs [32]. In addition, an increase in values from north to south can be seen on the map of the difference in insolation (figure 6c). These changes in surface insolation are due to the topography evolution that occurred during the study period, including the Holocene. An assessment of the difference in the corresponding DEMs showed that the subsidence of the Earth's crust took place in West Siberia (the median value of the difference between the DEMs was 230.7 m above sea level), which was more intense in a southerly direction (figure 7).

Two optimums were identified in which forests occupied new territories from south to north. The first optimum coincides with the time about 8,000 years ago, the second about 4,000 years ago. In the first optimum, the tundra biome began to be replaced by taiga with the formation of forest-tundra on almost the entire territory of the Urals, while during the second optimum, the taiga began to occupy an area from 56° to 65° north latitude, which demonstrates conditions more consistent with forest vegetation.

The insolation in May is two times higher than the insolation of the previous month, and 8 thousand years ago was higher than 4 thousand years ago by 5-8%. The insolation of June and July show a similar picture; the first climatic optimum accounts for more light than the second in these months. For the first climatic optimum, August is the beginning of a decrease in the incoming solar radiation, in contrast to the second climatic optimum. Insolation in August four thousand years ago is different from insolation in July, but it is still a bright month. The insolation in September and October continues to decrease gradually. Illumination 4 thousand years ago decreases not so sharply as eight thousand years ago.

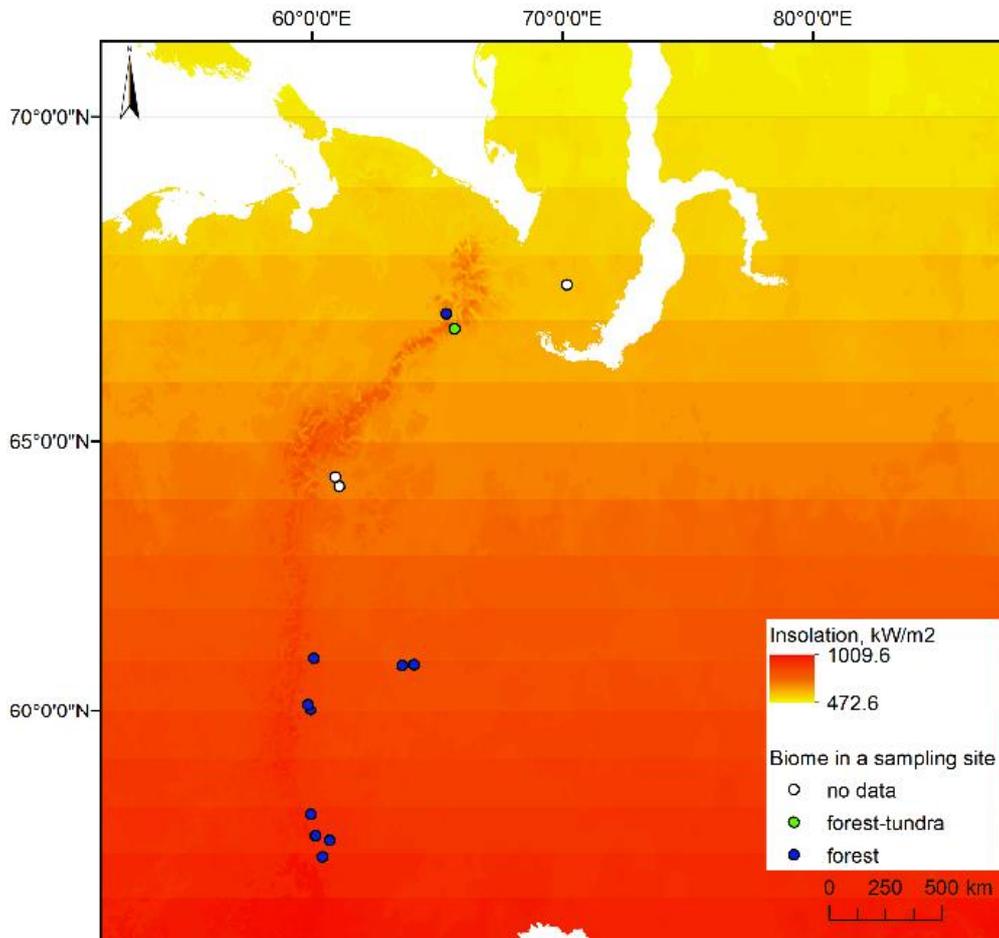


Figure 5. Annual surface insolation in the Urals and West Siberia for the recent period, and biomes sampling sites.

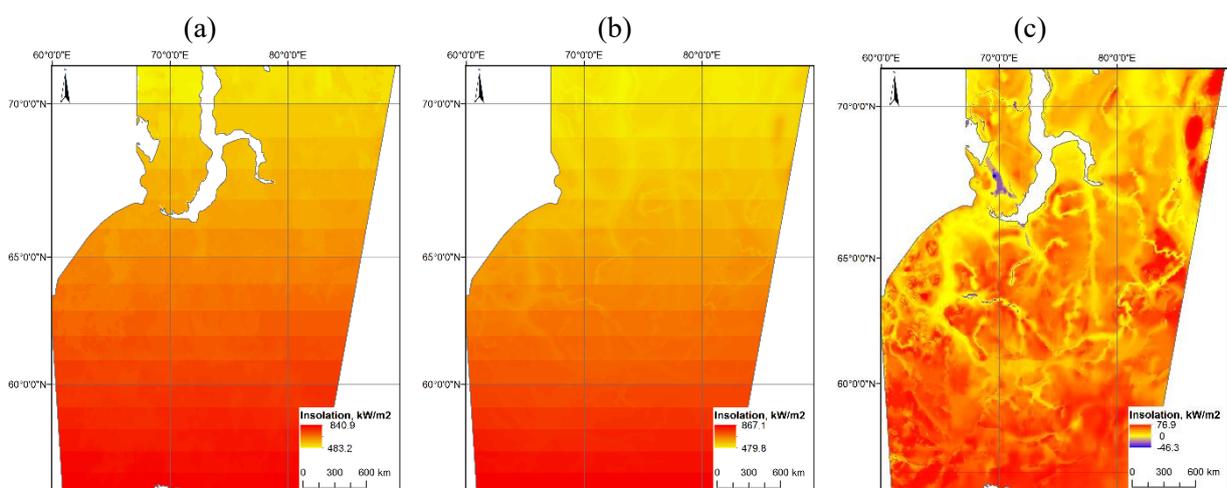


Figure 6. Annual insolation for the territory of the Eurasian subarctic: (a) the recent period, (b) the Pliocene era, (c) the difference in insolation between the Pliocene and the recent period

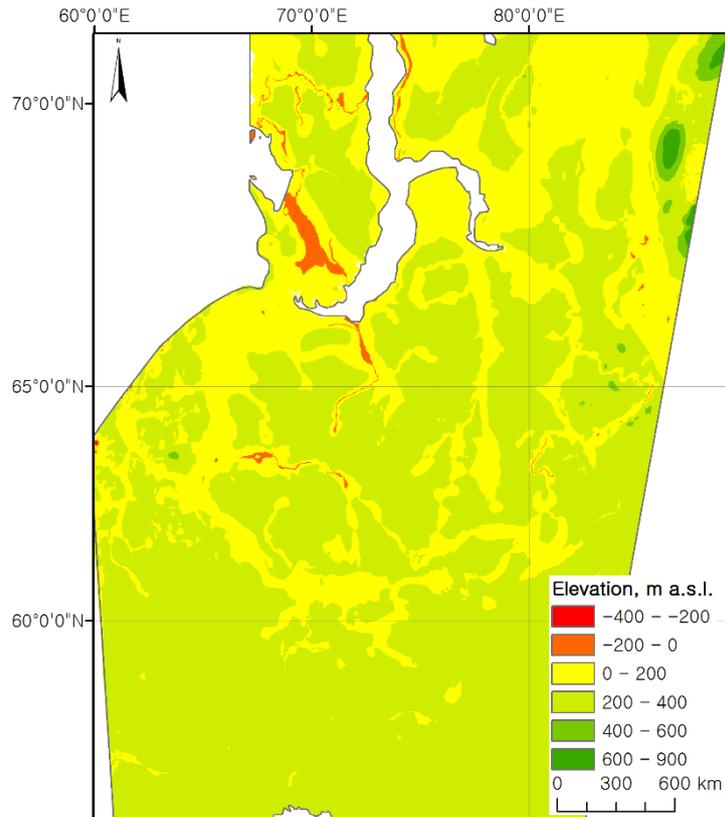


Figure 7. The difference between digital elevation models of the Pliocene and the recent period in West Siberia

4. Discussion

The peculiarity of insolation in the Holocene is that in January and February (figures 2a and 2b), insolation depends on latitude and varies little with time. In June and July (figures 2f and 3a), the dependence on latitude practically disappears, and insolation decreases with time. In the remaining months, there is restructuring from latitudinal dependence to time dependence and vice versa. This effect can be revealed from the data given in [33–37], but this was not emphasized, because considered longer time intervals.

According to the data on the origin of the main modern topographic elements [5], the formation of plains and plateaus in most of the West Siberian Plate, starting from the Pliocene, occurred under conditions of subsidence (from intense to weak) due to erosion processes, and the main features of the modern topography were formed in the Quaternary time. The period of formation of the modern Ural Mountains probably corresponds mainly to Pliocene-Quaternary times [38].

When interpreting the relationship between the subsidence of the crust and the insolation decrease in Western Siberia over the period from the Pliocene to the present, it is necessary to take into account that insolation is generally reduced with decreasing elevation. This is due to two reasons: elevated areas have more open viewsheds and here the optical depth of the atmosphere is lower [7]. Per contra, there is a directly proportional relationship between elevation and cloudiness [39], which partly compensates for the decrease in the optical depth of the atmosphere with elevation [7].

Determining the causes of the wider distribution of the taiga biome in the second half of the Holocene is the goal of future studies where it is necessary to use climatic parameters together with data on vegetation and insolation. At this stage, we can assume the following:

An increase in the number of months with increased insolation led to the spread of the taiga biome 4 thousand years ago to wider territories than 8 thousand years ago. This is probably due to the fact

that the number of months with a sufficient level of insolation is more important for forest vegetation, rather than the total temperature of the Earth, which was 8 thousand years ago higher than 4 thousand years ago [40], but did not lead to the abundant distribution of forests at latitudes from 55° to 70°.

5. Conclusions

In the study, we present new results about the influence of the insolation on the climate in the Urals and West Siberia in Holocene. We have shown that the variations of the mean monthly insolation in spring, summer, and autumn depend on the time significantly. In addition to the evolution of the Earth's orbit, one of the factors that influenced the change in insolation in West Siberia was the subsidence of the earth's crust starting from the Pliocene. The median value of the difference in insolation between the Pliocene and the recent period was 22.3 kW/m². We showed that an increase in the number of autumn months with high insolation correlates with the distribution of taiga biome. About 4 thousand years ago, the taiga biome was spread over a wider area than 8 thousand years ago.

In the future, we plan to describe the evolution of direct solar radiation flux at surface over 12 ka BP in the Eurasian Subarctic due to changes in the land surface topography that gives a possibility to investigate the insolation influence on the climatogenic dynamics accurately.

Acknowledgments

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